Name:

Introductory Optomechanical Engineering 421/521 – Fall 2016: Final Exam

One page of notes is allowed (single-side 8.5" x 11"). Some equations are provided. See page 12.
120 minutes.

1) Lens alignment (8)

Consider a 50 mm diameter meniscus BK7 lens with the following properties:

The lens is to be mounted in a barrel such that the convex surface is seated with ring contact in the barrel. The lens is measured to have 1 arcminute deviation (for centration defined by the outer cylindrical rim).

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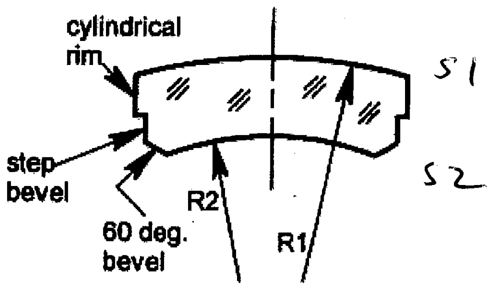


R1 = 200 mm convex

R2 = 160 mm concave

Ct = 15 mm

1 arcminute deviation for light through the center of the lens as defined by the cylindrical rim.

$n \cong 1.5$

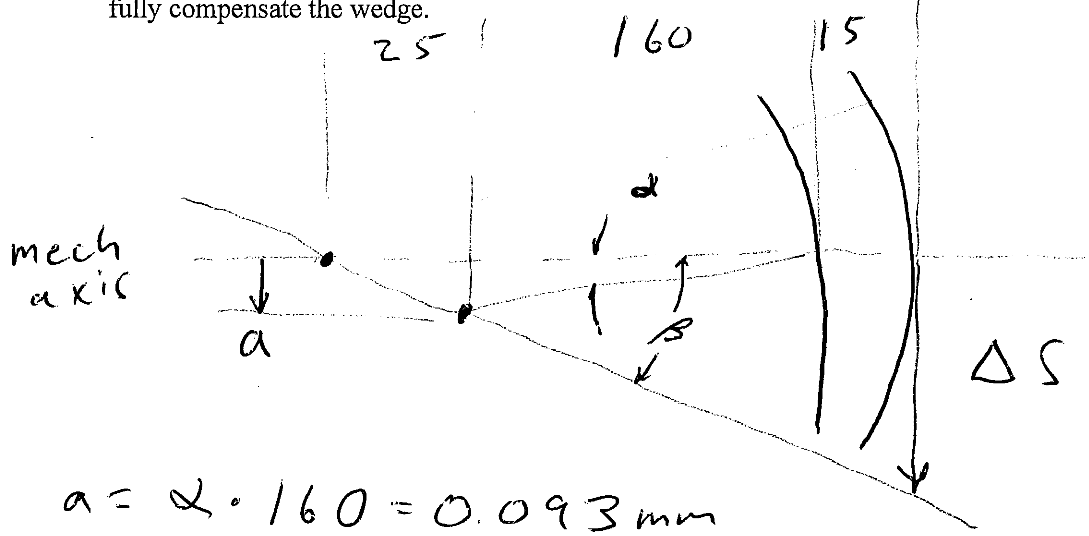
Calculate the wedge in the lens.

$\delta = (n-1)\alpha \qquad \alpha = 2\cdot\delta = 2\ \text{arcmin} \cong 0.58\ \text{mrad}$

Describe how to mount the lens to compensate for the wedge.

Decenter, rotating about S1 CoC

Provide a sketch and analysis to show quantitatively how much adjustment in the mounting is required to fully compensate the wedge.



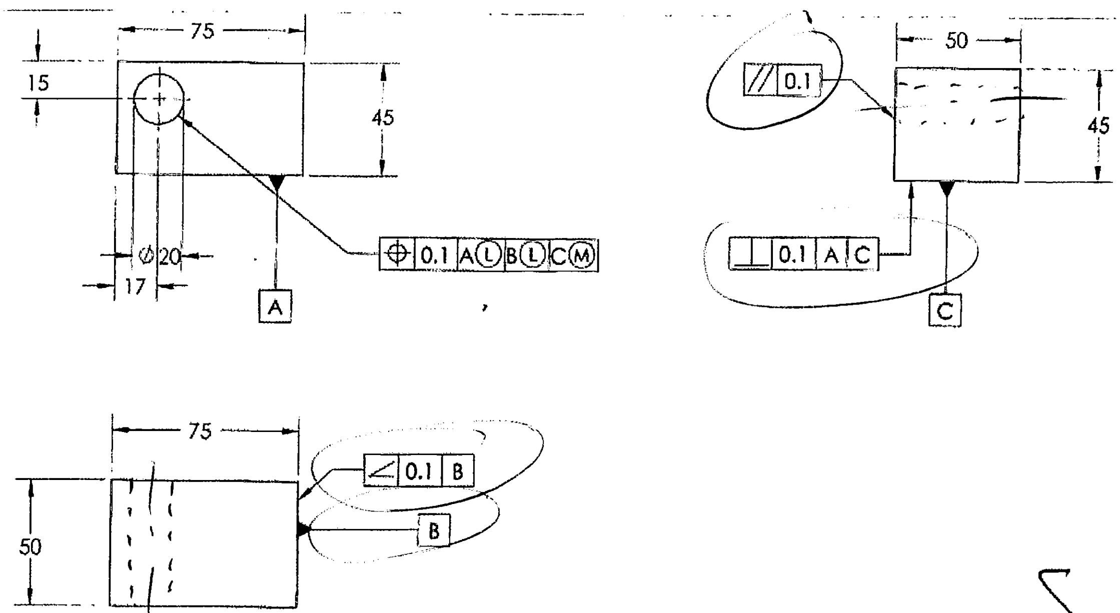
$a = \alpha \cdot 160 = 0.093\ \text{mm}$

$\beta = a/25 = 3.7\ \text{mrad}$

$\Delta S = 200 \cdot \beta = 0.74\ \text{mm}$

2) <u>Drawings (5)</u>

Find 5 mistakes in this drawing. Mark these on the drawing and explain each one.



1) over dimensioned

2) B has angle tolerance wrt B?

3) C has ⊥ tolerance wrt C?

4) A & C are the same

5) hole hidden lines

// has no datum.

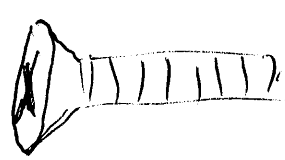
3) <u>(6) Hardware</u>

For the following hardware items, sketch the shape and provide a brief explanation about why this item may be used:

a) Socket head cap screw

General purpose fastener

b) Flathead screw



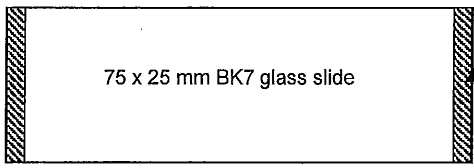
Makes flush

c) Belleville washers

spring washers

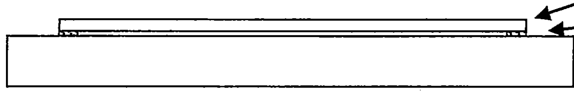
4) <u>Optical mount (15)</u>

A 75 x 25 x 0.8 mm BK7 microscope slide is bonded to an aluminum plate using RTV as shown. When observing specimens on this slide, we observe that focus changes with temperature due to bending of the slide. If the system is cooled 1° C, determine the **amount** and **direction** of the focus change.



Bond area is 25 x 4 mm on both sides

RTV properties
Shear modulus is 1 MPa
Shear strength is 0.5 MPa



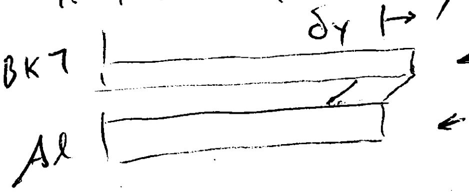
0.8 mm thick glass slide $\alpha = 7$ ppm/°C

0.1 mm thick RTV

Thick aluminum plate $\alpha = 24$ ppm/°C

Provide a clear definition for all assumptions and for each of the steps used to solve this.

1. thermal change, assume all strain in the bond



$\delta y = \Delta\alpha \frac{a}{2} \Delta T = 17 \cdot 37.5 \cdot 1 = .64 \mu m$

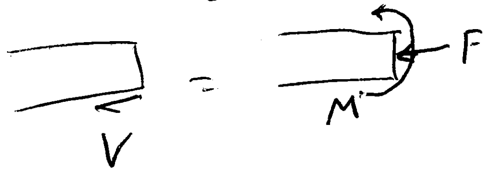
$\gamma = \delta y / t = \frac{0.64 \mu m}{100 \mu m} = 6.4$ mrad

2. Calculate stress, shear force from bond

$\tau = G \cdot \gamma = 1 \, N/mm^2 \cdot 0.0064 = 0.0064 \, N/mm^2$ (<< strength!)

$V = \tau A = 0.0064 \cdot 4 \cdot 25 = 0.64 N$

3. ~~Det~~ Decompose to determine moment on the glass

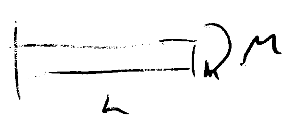


$F = V$

$M = V \, t/2 = 0.64 N \cdot .4 \, mm = 0.26 \, N \, mm$

4. Use moment to determine bending in glass

$\delta = \frac{ML^2}{2EI}$



$L = 37$ mm

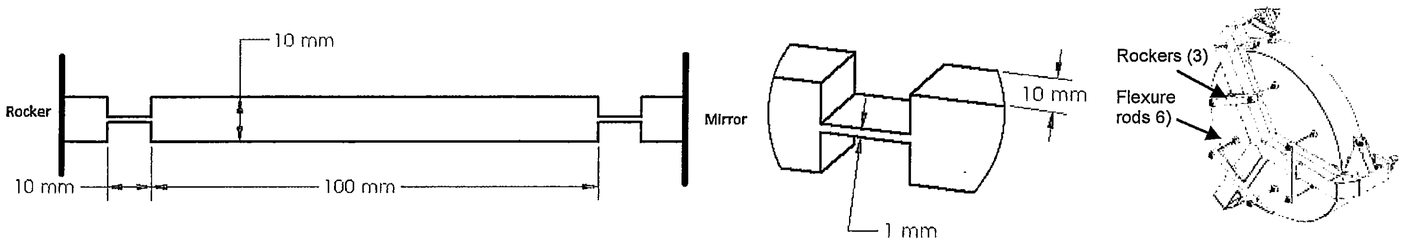
$E = 80,000 \, N/mm^2$

$I = \frac{1}{12} 25 \cdot 0.8^3 = 1.07 \, mm^4$

$= \frac{0.26 \cdot 37^2}{2 \cdot 80,000 \cdot 1.07} \frac{N \, mm \, mm^2 \, mm^2}{N \cdot mm^4}$

$=$ ~~2.4 μm~~ $= 2.1 \mu m$

5) <u>Flexure analysis (20)</u> Consider the case of a 500 mm diameter, 50 mm thick Zerodur mirror, supported axially using six rods with blade flexures at the ends, connected by three rocker arms. The axial flexure rods are made of 6061-T6 aluminum, 10 cm long, 1 cm x 1 cm square cross section with 1 mm thick, 10 mm long flexure blades machined at both ends as shown below:



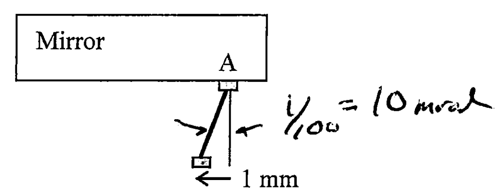
A) Calculate the angular stiffness for each 1 mm thick blade in the soft direction (in N-mm/mrad).

$$\Delta\theta = \frac{ML}{EI} \qquad K = \frac{M}{\Delta\theta} = \frac{EI}{L} = \frac{70{,}000 \cdot 10 \cdot 1^3}{12 \cdot 10}$$

$$= 5800 \text{ N}\cdot\text{mm/rad}$$

$$= 5.8 \frac{\text{N}\cdot\text{mm}}{\text{mrad}}$$

B) Calculate the moment imparted into the mirror due to a 1 mm alignment error in one end of the flexure rod, coupled with the flexure stiffness.



$$5.8 \frac{\text{N}\cdot\text{mm}}{\text{mrad}} \cdot 10 \text{ mrad}$$

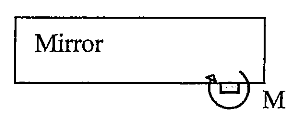
$$= 58 \text{ N}\cdot\text{mm}$$

C) Calculate the elastic range of the flexure

$$\sigma = \frac{My}{I} \qquad \sigma_{max} = \frac{M\, t/2}{I} = \frac{t}{2I} \cdot \frac{EI\,\Delta\theta}{L} =$$

$$\theta_y = 2 \cdot \frac{L}{t} \frac{\sigma_Y}{E} = 2 \cdot \frac{10}{1} \cdot \frac{40 \text{ ksi}}{10{,}000 \text{ ksi}} = 0.08 \text{ rad}$$

Finite element unit load analysis shows 12 nm rms surface deflection when 1 N-mm moment is applied to the mirror at point A at the attachment point of an axial flexure.



D) Calculate mirror distortion due to the 1 mm flexure alignment error above.

Scale it $\quad 12 \text{ nm rms} \cdot 58 = 700 \text{ nm rms}$

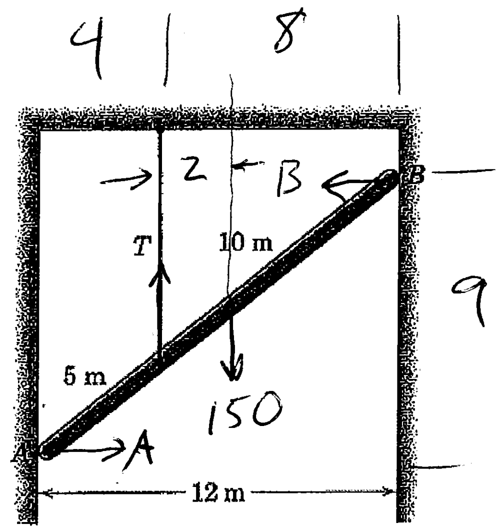
E) Assume isotropic behavior and estimate the mirror surface deflection for the case where the system assembly includes random errors of 1 mm in each of the 6 flexure rods.

6 contributions, each 700

total RSS = $700 \cdot \sqrt{6} = 1.7 \mu\text{m rms}$

6) Statics (5)

The uniform 15-m pole has a mass of 150 kg and is supported by its smooth ends against the vertical walls and by the tension *T* in the vertical cable. Compute the reactions at *A* and *B*.



$\Sigma F_x = 0 \quad A = B$

$\Sigma F_y = 0 \quad T = W = 150 \text{ kg}$

ΣM_o

Force couple

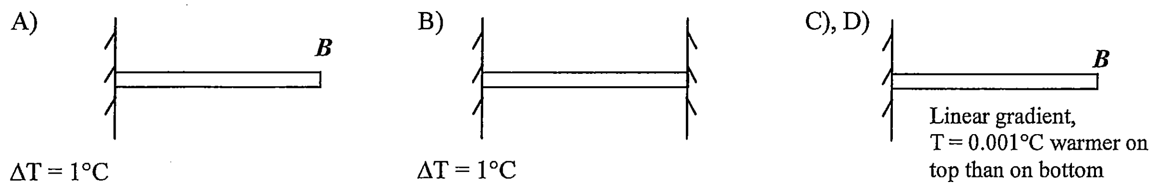
$150 \cdot 2 = A \cdot 9$

$B = A = 33.3 \text{ kg} = 327 N$

$T = 150\text{kg} = 1470 N$

7) <u>Thermal stress and strain (12)</u> Consider a bar made of aluminum 10 cm long, 1 cm x 1 cm cross section. Determine the following, using the geometry shown in the sketches below:

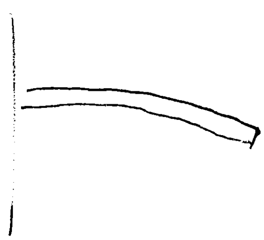
A) Motion of point ***B*** if the bar is heated 1°C, and allowed to expand
B) Stress in the material if the bar is heated 1°C while rigidly constrained as shown.
C) Motion of point ***B*** for the case where a thermal gradient is applied, with the top of the bar 0.001°C warmer than the bottom.
D) How many Watts of thermal power are required to maintain this 0.001° gradient.



A: $\Delta L = \alpha L \Delta T = 24\,ppm/°C \cdot 1°C \cdot 100\,mm = 2.4\,\mu m$

B: $\sigma = \alpha E \Delta T = 24\,ppm/°C \cdot 70\,GPa \cdot 1 = 1.7\,MPa$

C:



$$\frac{\Delta\theta}{\Delta\xi} = \frac{1}{R} = \alpha \frac{dT}{dy} = 24E\text{-}6 \cdot \frac{.001}{10} = 2.4E\text{-}9\ mm^{-1}$$

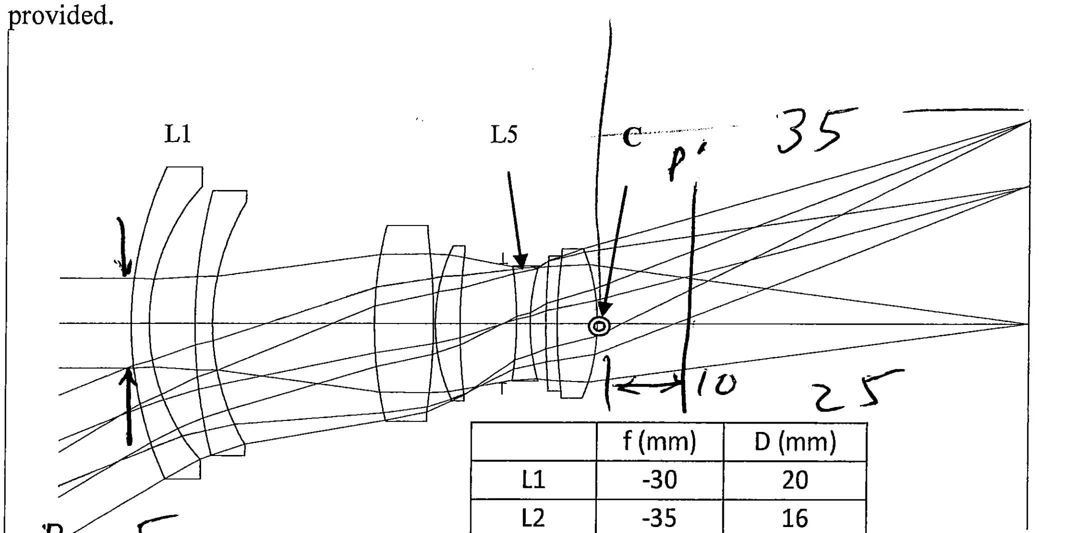
$$\delta y = \frac{l^2}{2R} = \frac{100^2}{2} \cdot 2.4E\text{-}9 = 12\ nm$$

D) $H = Q \cdot A = \frac{A \lambda \Delta T}{t} = \frac{(.1)(.01) \cdot 170 \cdot .001}{(.01)}$ $\quad \frac{m^2 \cdot W\,K}{m \cdot K}$

$= 17{,}0\ mW$

8) <u>Line of sight (8)</u>

Consider the following objective lens. The system has 5 mm entrance pupil diameter and 25 mm EFL, 35 mm BFD (Back Focal Distance), and ± 31° FOV. The diameter and focal length of each lens element are provided.



	f (mm)	D (mm)
L1	-30	20
L2	-35	16
L3	28	11
L4	28	9
L5	-12	6
L6	20	8

$F_\# = \frac{25}{5} = 5$

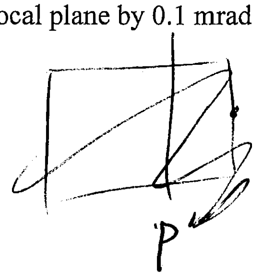
$B = 5$

a) Calculate the image motion for 1 μm decenter of L1.

$\varepsilon = B \cdot F_\# \cdot \Delta\theta \qquad \Delta\theta = \frac{\Delta s}{f}$

$= B \cdot F_\# \cdot \frac{\Delta s}{f} = 5 \cdot 5 \cdot \frac{1\mu m}{30} = 0.83 \mu m$

b) Calculate the image motion for the case where the lens assembly is rotated with respect to the focal plane by 0.1 mrad about point C.



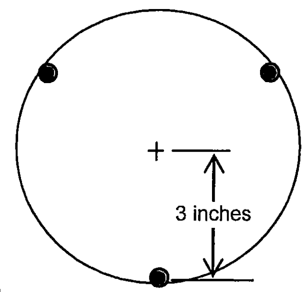
0.1 mrad · 10 mm = 1 μm

9) Mirror mount (21) A 6 inch diameter, 1 inch thick Zerodur mirror is bonded to a thick aluminum plate using 0.1" thick RTV elastomeric adhesive. Three small 0.5" diameter bonds are made at the edge of the mirror.

$\rho = 0.1$ lb/in^3

This adhesive has

- 100 psi shear modulus
- 100,000psi bulk modulus
- 100 psi adhesive shear strength



a) Calculate the weight of the mirror and use this to calculate the shear force per bond when the mirror is supported with the optical axis horizontal (on edge).

$W = \rho \cdot V = 0.1 \cdot \frac{\pi 6^2}{4} \cdot 1 = 2.8$ lb

3 bonds, equally loaded $V = 2.8/3 = 0.94$ lb

b) Determine the shear stress in the bonds for a 20 G shock load in the shear direction. Compare with the strength.

20 G : $V = 0.94 \cdot 20 = 18.8$ lb/bond

$A_{bond} = \frac{\pi (.5)^2}{4} = 0.2$ in^2 ≈ 96 psi Fail!

$\tau = V/A$

c) Determine the lateral deflection of the mirror due to its weight as it is supported as above.

$$\Delta y = \frac{Vt}{GA} = \gamma \cdot t = \frac{\tau}{G} \cdot t = \frac{(0.94)\cdot(0.1)}{100 \cdot (0.2)} = .0047''$$

d) Calculate the resonant frequency of the mirror for this mode.

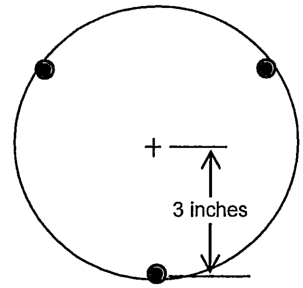
$$f_n = \frac{1}{2\pi} \omega_n = \frac{1}{2\pi}\sqrt{\frac{g}{\delta_{sw}}} = \frac{1}{2\pi}\sqrt{\frac{386 \text{ in/s}^2}{.0047}} = 45 \text{ Hz}$$

Continued from problem 9.) The 6 inch diameter, 1 inch thick Zerodur mirror is bonded to a thick aluminum plate using 0.1" thick RTV elastomeric adhesive. Three small 0.5" diameter bonds are made at the edge of the mirror.

This adhesive has
- 100 psi shear modulus
- 100,000psi bulk modulus
- 100 psi adhesive shear strength

$\alpha_{zerodur} = 0$

$\alpha_{AL} = 24$



$\Delta\alpha = 24$ ppm

e) Calculate the adhesive shear strain for 20°C change in temperature, coupled with the expansion of the mirror and the aluminum mounting interface.

$$\gamma = \frac{3'' \cdot 24\,ppm \cdot 20^\circ C}{0.1''} = 14.4 \text{ mrad}$$

14,400 E-6

f) Calculate the shear stress in the adhesive for the above 20°C temperature change. Compare this to the adhesive strength

$\tau = G \cdot \gamma = 1.4$ psi $\ll 100$

SF = 70!